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The University of Texas

Report No. 65

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Dielectric Constant Measurements at
8.6 Millimeter Wavelength

ELECTRICAL ENGINEERING RESEARCH LABORATORY

THE UNIVERSITY OF TEXAS

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DIELECTRIC CONSTANT MEASUREMENTS AT 8.6 MILLIMETER WAVELENGTH

by

Paul Hertel, Jr.
A. W. Straiton
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ABSTRACT

The dielectric constant and conductivity of water, ethyl alcohol and a soil sample were measured at 8.6 millimeters by sending the waves through an open sample of each material. The results of the measurements are as follows:

Material	Temperature °C	Dielectric Constant	Conductivity mho/meter
Distilled water	30	21.4	60.4
Distilled water	23.5	22.6	55.3
Saturated salt solution	25	20.6	53
Tap water	24	23.7	55.6
Dry soil (as found)	25	2.98	0.506

I. INTRODUCTION

This report describes dielectric constant measurements made at a wavelength of 8.6 millimeters. The general method used was that of passing energy of this wavelength through a sample of the dielectric in an open glass container. The thickness of the sample was varied by adding small known volumes and determining the resulting phase shift and attenuation.

The values of the dielectric and loss constants of water and soil are of interest to radio engineers because of their effects on the reflection and transmission of waves of this frequency.

The basic millimeter equipment was that used in previous studies of the propagation characteristics of these waves over land and water. This equipment was described in connection with these tests [1] and only the application of this apparatus to the dielectric studies will be given in this report.

Dielectric studies at 3.2 centimeter were made by this Laboratory in 1947, using similar techniques [2].

II. ELECTRIC FIELD RELATIONS

The electrical characteristics of any homogeneous dielectric or semi-conductor may be defined in terms of its permittivity ε, permeability μ, and conductivity σ. The permeability of all common dielectrics is sufficiently close to that

- 1 -

of free space that it may be considered equal to the free space value. The conductivity may result from free ions in the dielectric, as well as from the relaxation mechanism described by Debye [3], and will in general be a function of frequency. It is often convenient to include the conductive characteristics of a dielectric as a component of the dielectric constant. The permittivity then becomes a complex quantity defined by

$$\varepsilon_e = \varepsilon' - j\varepsilon'' = \varepsilon' + \frac{\sigma}{j\omega} = \varepsilon' \left(1 + \frac{\sigma}{j\omega\varepsilon'}\right) \tag{1}$$

The electric intensity of a plane polarized wave moving in the positive Z direction may be expressed as the real part of

$$E = Ae^{j\omega t} e^{-\overline{}Z}. \tag{2}$$

where ω is the angular frequency ($2\pi f$) and

$$\overline{} = \alpha + j\beta = j\omega\sqrt{\mu\varepsilon_c} \tag{3}$$

is the propagation constant determined by the characteristics of the dielectric medium. The relations presented in (2) and (3) result from the solution of Maxwell's field equations and are given here without proof. For their derivation the reader is referred to Stratton [4]. From (2) and (3) we have

$$E = Ae^{-\alpha Z} e^{j(\omega t - \beta Z)}. \tag{4}$$

It is seen that the wave amplitude decreases exponentially in the positive Z direction in a manner determined by α. The phase is determined by the time phase factor ωt and the space phase factor βz.

From (1) and (3) we may obtain

$$\overline{} = \alpha + j\beta = j\omega\sqrt{\mu\varepsilon'\left(1 + \frac{\sigma}{j\omega\varepsilon'}\right)}. \tag{5}$$

Solving for ε' and σ we have

$$\varepsilon' = \frac{\beta^2 - \alpha^2}{\omega^2\mu} \tag{6}$$

$$\sigma = \frac{2\beta\alpha}{\omega\mu} \tag{7}$$

In the relations above ε' is to be identified as the permittivity and μ' as the permeability. In the m.k.s. system the permittivity of free space is $k' = 8.854 \times 10^{-12}$ farads/meter. The term dielectric constant is understood to be the relative permittivity based on the permittivity of free space as one unit. Dielectric constants will be indicated by k and permittivity by ε. Then,

$$k_c = \frac{\varepsilon' - j\varepsilon''}{\varepsilon_o} = k' - jk'' \tag{8}$$

then

$$k' = \frac{\varepsilon'}{\varepsilon_0} = \frac{\beta^2 - \alpha^2}{\omega^2 \mu \varepsilon_0} \tag{9}$$

and

$$k'' = \frac{\varepsilon''}{\varepsilon_0} = \frac{\sigma/\omega}{\varepsilon_0} = \frac{2\beta\alpha}{\omega^2 \mu \varepsilon_0} \tag{10}$$

But $\omega^2 \mu \varepsilon_0 = 2\pi/\lambda_0$, where λ_0 is the wavelength in free space, hence

$$k' = \left(\frac{\lambda_0}{2\pi}\right)^2 (\beta^2 - \alpha^2) = 0.00137 \, (\beta^2 - \alpha^2) \tag{11}$$

and

$$k'' = \frac{1}{2}\left(\frac{\lambda_0}{\pi}\right)^2 \beta\alpha = 0.00274 \, \beta\alpha \tag{12}$$

$$\sigma = \omega \varepsilon_0 k'' = 1.94 \, k'' \tag{13}$$

where α and β are measured in nepers per meter and radians per meter respectively.

III. EFFECT OF REFLECTION OF SIGNAL TRANSMISSION

Relations derived previously allow k' and k'' to be calculated once the complex propagation constant is determined. Fixed transmitting and receiving antennas are placed external to the sample as shown in Figure 1. This arrangement allows attenuation and phase shift to be determined as a function of sample thickness provided consideration is given to reflection effects and the change of path length in the air on the receiver side of the sample.

Consider the sample and antenna arrangement shown in Figure 1 for which it is desired to derive relations expressing the magnitude and phase of the received signal as a function of the variable sample thickness L and the constants of the system. The following reasonable assumptions are made: (1) The wave returned from the glass has a negligible effect upon the wave transmitted. This condition is met by use of an attenuator between the source and the transmitting horn. (2) The reflection from the receiver may be neglected. (3) The loss in the air is negligible over the small path length considered. The complex wave in each region may be written in terms of an advancing and a reflected component. [5]. Hence, in region 1

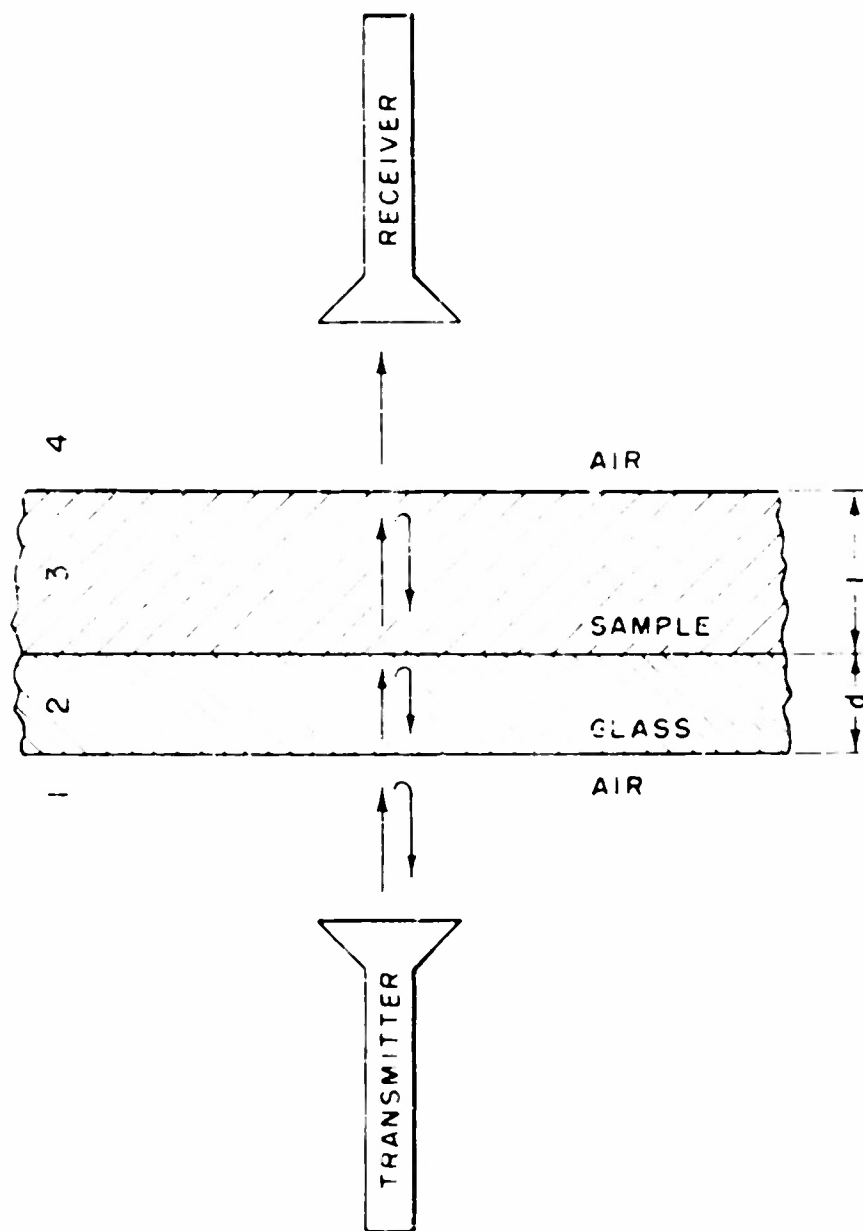$$E_x = A_1 e^{-j\beta_1 Z} + B_1 e^{j\beta_1 Z} \tag{14}$$

FIGURE 1

BASIC FREE WAVE MEASURING ARRANGEMENT

$$H_y = \frac{1}{n_1}\left[A_1 e^{-j\beta_1 Z} - B_1 e^{j\beta_1 Z}\right] \qquad (15)$$

In region 2

$$E_x = A_2 e^{-\Gamma_2 Z} + B_2 e^{\Gamma_2 Z} \qquad (16)$$

$$H_y = \frac{1}{n_2}\left[A_2 e^{-\Gamma_2 Z} - B_2 e^{\Gamma_2 Z}\right] \qquad (17)$$

In region 3

$$E_x = A_3 e^{-\Gamma_3(Z-d)} + B_3 e^{\Gamma_3(Z-d)} \qquad (18)$$

$$H_y = \frac{1}{n_3}\left[A_3 e^{-\Gamma_3(Z-d)} - B_3 e^{\Gamma_3(Z-d)}\right] \qquad (19)$$

In region 4

$$E_x = A_4 e^{-j\beta_4(Z-d-L)} \qquad (20)$$

$$H_y = \frac{A_4}{n_4} e^{-j\beta_4(Z-d-L)} \qquad (21)$$

where E and H are the electric and magnetic components of the wave respectively, and $n = \sqrt{\frac{\mu}{\varepsilon_c}}$ is the intrinsic impedance of the dielectric. A and B are constants depending upon the amplitude of the transmitted wave and the boundary conditions. Numerical subscripts indicate the region to which the indicated quantity belongs.

The tangential components of the waves must be equal at the boundaries of the dielectrics. By equating the tangential components we may write;

At the 1-2 boundary $Z = 0$ and

$$A_1 + B_1 = A_2 + B_2 \qquad (22)$$

$$\frac{1}{n_1}(A_1 - B_1) \quad \frac{1}{n_2}(A_2 - B_2) \qquad (23)$$

At 2-3 boundary $Z = d$ and

$$A_2 e^{-\Gamma_2 d} + B_2 e^{\Gamma_2 d} = A_3 + B_3 \qquad (24)$$

$$\frac{1}{n_2}\left(A_2 e^{-\Gamma_2 d} - B_2 e^{\Gamma_2 d}\right) = \frac{1}{n_3}(A_3 - B_3) \qquad (25)$$

At 3-4 boundary $Z = d + L$ and

$$A_3 e^{-\Gamma_3 L} + B_3 e^{\Gamma_3 L} = A_4 \tag{26}$$

$$\frac{1}{n_3}\left(A_3 e^{-\Gamma_3 L} - B_3 e^{\Gamma_3 L}\right) = \frac{A_4}{n_4} \tag{27}$$

Equations (22) to (27) comprise a group of six simultaneous equations in seven unknowns. The relation of A_4 to A_1 may be determined from these equations as

$$A_1/A_4 = \frac{1}{8n_1 n_2 n_3}\left[(n_1+n_2)(n_2+n_3)(n_3+n_4)\ e^{\Gamma_2 d + \Gamma_3 L} \right.$$

$$+ (n_2+n_1)(n_3-n_2)(n_4-n_3)\ e^{\Gamma_2 d - \Gamma_3 L}$$

$$+ (n_2-n_1)(n_3-n_2)(n_4+n_3)\ e^{-\Gamma_2 d + \Gamma_3 L}$$

$$\left. + (n_2-n_1)(n_3+n_2)(n_4-n_3)\ e^{-\Gamma_2 d - \Gamma_3 L} \right] \tag{28}$$

The constant $e^{\Gamma_2 d}$ depends on the electrical characteristics and thickness of the glass. Hence, we may write

$$A_1/A_4 = a e^{-\Gamma_3 L} + b e^{\Gamma_3 L} \tag{29}$$

Where for a given sample and container, a and b are constants defined by

$$a = \frac{(n_2+n_1)(n_3-n_2)(n_4-n_3)e^{\Gamma_2 d} + (n_2-n_1)(n_3+n_2)(n_4-n_3)\ e^{-\Gamma_2 d}}{8n_2 n_3 n_4} \tag{30}$$

$$b = \frac{(n_2+n_1)(n_3+n_2)(n_3+n_4)e^{\Gamma_2 d} + (n_2-n_1)(n_3-n_2)(n_4+n_3)\ e^{-\Gamma_2 d}}{8n_2 n_3 n_4} \tag{31}$$

Then

$$A_4/A_1 = \frac{1}{a e^{-\Gamma_3 L} + b e^{\Gamma_3 L}} = \frac{e^{-\Gamma_3 L}}{(b + a e^{-2\Gamma_3 L})} \tag{32}$$

and

$$\ln(A_4/A_1) = -\Gamma_3 L - \ln(b + a e^{-2\Gamma_3 L}) \tag{33}$$

Taking the derivative of $\ln A_4/A_1$ with respect to L we obtain

$$\frac{d}{dL} \ln A_4/A_1 = \Gamma_3 + \frac{2\Gamma_3\, ae^{-2\Gamma_3 L}}{(b + ae^{-2\Gamma_3 L})} = \Gamma_3\left(1 - \frac{2ae^{-2\Gamma_3 L}}{b + ae^{-2\Gamma_3 L}}\right) \qquad (34)$$

Γ is defined as $\alpha + j\beta$. Hence,

$$\frac{d}{dL}\left(\ln \frac{A_4}{A_1}\right) = (-\alpha - j\beta)\left[1 - \frac{2ae^{-2\alpha L - 2j\beta L}}{b\,1 + \frac{a}{b}\,e^{-2\alpha L - 2j\beta L}}\right] \qquad (35)$$

It is desired to determine the conditions under which the right side of (35) above reduces to approximately $-\alpha - j\beta$. This condition requires that

$$\frac{2ae^{-2\alpha L - 2j\beta L}}{b + ae^{-2\alpha L - 2j\beta L}} << 1. \qquad (36)$$

Obviously this condition exists when $ac^{-2\alpha L}$ is small compared to b. The expressions defining a and b are given in (30) and (31). At millimeter wavelengths $\Gamma_2 d$ for moderate thickness of glass will be sufficiently large so that $e^{-\Gamma_2 d}$ will be small compared to $e^{+\Gamma_2 d}$. The terms involving the negative exponentials in the expressions for a and b may then be neglected. It is seen then that b will be larger than a and greater than unity, regardless of the values of the impedances. It is seen that the numerator of (36) is a function which oscillates about zero at a rate determined by 2β and decays at a rate determined by 2α as L increases. The denominator oscillates about the value b as L increases and may never be negative since $a/b < 1$. Therefore, the left hand member of (36) oscillates about zero as L varies and has a maximum amplitude of $2a/(a + b) < 1$. This function is similar to a damped sine wave.

IV. EXPERIMENTAL DETERMINATION OF α AND β

The attenuation constant α may be determined experimentally by measuring the ratio of some arbitrary reference level to the received signal level and plotting the logarithm of this ratio as a function of L. The slope of a straight line drawn through the mean of these points determines α. The amount of oscillation of the experimental points about this mean line is an indication of the significance of the oscillating term in (35). The oscillation will generally die out rapidly as L is increased.

The phase constant β may be determined by comparing the phase of the signal transmitted through the sample to a reference signal transmitted over a fixed path.

Measurement of phase shift with increasing L will allow the phase constant β to be determined provided correction is made for the change in path length in air as L is varied.

The free wave measurement method considered above was used to obtain dielectric constant data for several samples. The experimental procedure employed and the data obtained are given in the following section.

V. ATTENUATION MEASUREMENT

A block diagram of the measuring equipment is given in Figure 2. The dielectric samples were placed in a circular, straight-sided, flat-bottomed, glass container. The measurement procedure required changing the sample thickness in small known increments. This was accomplished with the liquid samples by adding measured volumes from a standard chemical burette. This technique allowed accurate measurement of small volumes and hence small increments of height. Calibration of the container, in cc of volume per mm of height, was accomplished by filling the container with a measured volume of water and accurately measuring the height with a millimeter rule.

At the start of the measurements the container was placed on the transmitting horn antenna and sufficient liquid was added to cover the bottom with a thin layer. This assured an even flat surface of liquid at the beginning of the test. After a suitable warm-up period the oscillator was adjusted to 8.6 mm wavelength and for maximum sensitivity. The receiver reference level was set by adjusting attenuator 1. The liquid sample was then added in constant-volume increments. Attenuator 1 was adjusted after each sample addition to return the signal strength indicator back to its previous reference position. Each attenuator setting was recorded. The attenuation in db as a function of added volume was plotted and a straight line was drawn through the average of these points as illustrated in the appendix. The attenuation constant in nepers per meter was then determined from the slope of this line and the calibration of the container. Two or more sets of attenuation data were obtained for each sample in nearly all of the cases.

VI. PHASE SHIFT MEASUREMENT

The phase shift measurement required the use of a calibrated phase shifter which was constructed from a resistance card attenuator. A polystyrene card was inserted into the guide by a screw which required about 5 turns to cover the total range of phase shift of about 0.8 wavelength. The polystyrene card was experimentally shaped for minimum reflection. The equipment was set up for phase shift measurements as shown in Figure 2. The signal from the oscillator was divided by the magic tee. The signal through branch 1 feeds from the transmitter horn through the sample and into the receiving horn. The signal in branch 2 feeds through an attenuator and a calibrated phase shifter. The two signals are again joined in the receiving guide at the directional coupler. The two signals add vectorially at the directional coupler and their combined strength is read on the receiver signal strength meter. Minimum meter reading is obtained when their phases differ by 180 degrees. This minimum may be obtained by adjusting the phase shifter in branch 2. It is desired to obtain the position of the phase shifter at minimum
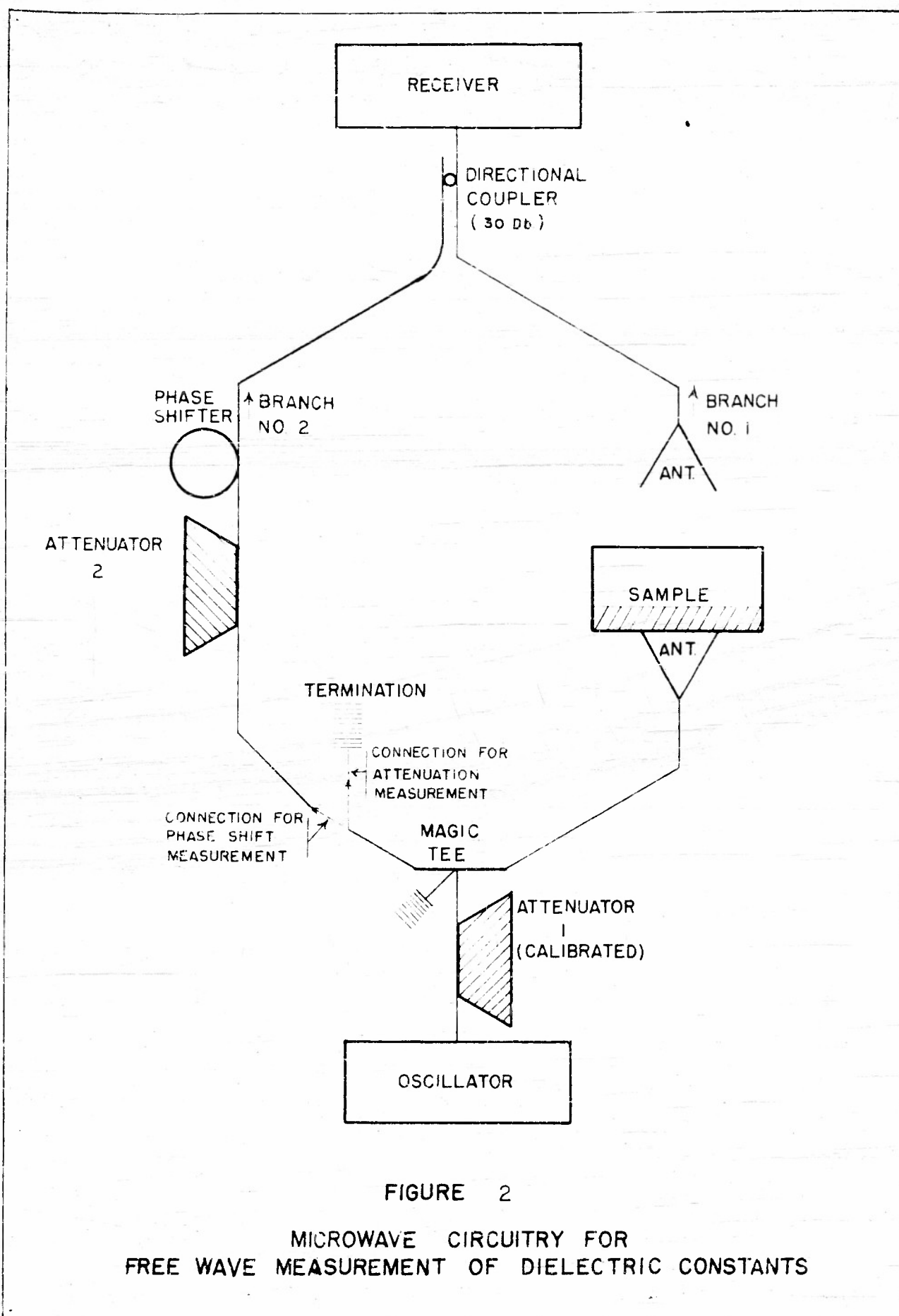
FIGURE 2

MICROWAVE CIRCUITRY FOR
FREE WAVE MEASUREMENT OF DIELECTRIC CONSTANTS

to as high precision as possible. The sharpest minimum is obtained when the two signals are of equal strength when combined at the directional coupler. In order to obtain reasonable precision it was found necessary to adjust attenuator 2 after every two or three changes of sample height. Attenuator 2 also caused considerable change in phase shift with each change of attenuation. For this reason phase shifter readings were taken before and after each addition of sample, and attenuator 2 was left unchanged until both readings were taken. The minimum was rather broad, particularly if the signals were not near the same strength. For this reason the phase shifter was not read at minimum but at equal signal strength points on each side of minimum. These two readings determined two phase shift points on the calibration curve of the phase shifter. The average of these two phase shifts was recorded. Readings were taken before and after each addition of sample. The difference in the two values of phase shift so obtained is equal to the phase shift in the added sample over the phase shift in an equal distance in air.

Since the range of the phase shifter was only 0.8 wavelength, a complete phase shift run was not possible without adjustment of the path length. This was accomplished by placing shims under the support holding the transmitting horn. By making small changes in the path length between the two horns it was possible to keep the phase readings in the linear range of the phase shifter at all times.

The measurement procedure used for the soil samples was similar to that for liquid samples, except that larger volume increments were used and a graduated cylinder was used for volume measurement instead of the burette.

VII. TEMPERATURE MEASUREMENT

The measurement method used did not allow convenient regulation of the sample temperature and no regulation was attempt ... However, all liquid samples were allowed to reach room temperature before measurements were made. The sample temperature was measured immediately before beginning each set of measurements. The temperatures given are estimated to be accurate to within $\pm 1 \degree C$.

VIII. DETERMINATION OF k_0 FROM DATA

Attenuation and phase shift data were obtained as described above. Attenuation in db and phase shift in wavelengths were plotted as a function of added volume. These curves are given in the appendix. The height calibration of the container was determined to be: height change = 0.00366 cm per cc of added volume. From these data the phase constant β was determined in radians per meter and the attenuation constant α was determined in nepers per meter. β_d so determined is the difference between the shift in one meter of the sample and the shift in one meter of air. The total shift was then determined from

$$\beta = \beta_d + \beta_{air} = \beta_d + \frac{2\pi}{\lambda_o} \tag{37}$$

where λ_o is the wavelength in air in meter units. Once the propagation constants were obtained, the complex dielectric constant and conductivity were calculated from equations (11), (12) and (13).

IX. THEORETICAL VALUES OF k_o FOR WATER

Unfortunately none of the dielectric theories proposed has been completely satisfactory in explaining the observed behavior of all dielectrics. It has been shown by numerous experimenters, however, that the measured dielectric characteristics of many polar molecules, and specifically water, are in close agreement with values given by (38) and (39), provided proper choices of the values of the several parameters are made. From the theory of Debye [3] the components of the complex dielectric constant are written as

$$k' = \frac{k_s - k_o}{1 + x^2} + k_o \qquad (38)$$

$$k'' = \left(\frac{k_s - k_o}{1 + x^2}\right)x + \frac{\sigma_i}{\omega} \qquad (39)$$

where $x = \omega\tau$, ω is the angular frequency, τ is the relaxation time in seconds, k_o is the dielectric constant resulting from the atomic and electronic polarization (approximately that measured at light frequencies) k_s is the static or d-c dielectric constant, and σ_i is the conductivity due to the ions in solution.

If these relations may be assumed to be qualitatively correct, then independent measurement of k_s, k_o, and σ_i will allow these parameters to be determined. The remaining parameter x is determined by the relaxation time which may be chosen for proper placement of the region of dispersion as determined by experiment. Saxton and Lane [6] followed this procedure to obtain the curves of k' and k'' as a function of frequency shown in Figure 3. These curves show the values predicted by this method are in close agreement with measured values. They have also applied the procedure to define the characteristics of salt water solutions with particular emphasis on sea water. In earlier work [7] they assumed k_s to be independent of the salt concentration at constant temperature. They have later shown [6] that closer agreement with measured values is possible if both k_s and τ are considered a function of the concentration of the ions of the salt. A drop in k_s with ionization is to be expected due to the very high fields in the vicinity of the ions, which will reduce the ability of some of the molecules to contribute to the polarization by orientation.

X. MEASURED VALUES OF k_c FOR WATER

Experimental results are given in Table I and are compared with theoretical values obtained using (38) and (39). The values of the various parameters are obtained from the work of Saxton and Lane [6]. Plots of theoretical values of k' and k'' as a function of frequency for several temperatures and salt concentrations are given in Figure 3 to show the effect of these parameters. The frequency of measurement (34,900 mc/s) is indicated by F_m on the frequency scale of the curves. At this frequency, the curves of Figure 3 indicate that k' may be expected to increase with increasing temperature. This behavior is opposite that to be expected at frequencies below the region of dispersion.

At 30°C the value obtained for k' for distilled water was low by about 12% of that predicted by the Saxton theory. However, the value obtained for k'' differed from the theoretical value by only 2.5%.
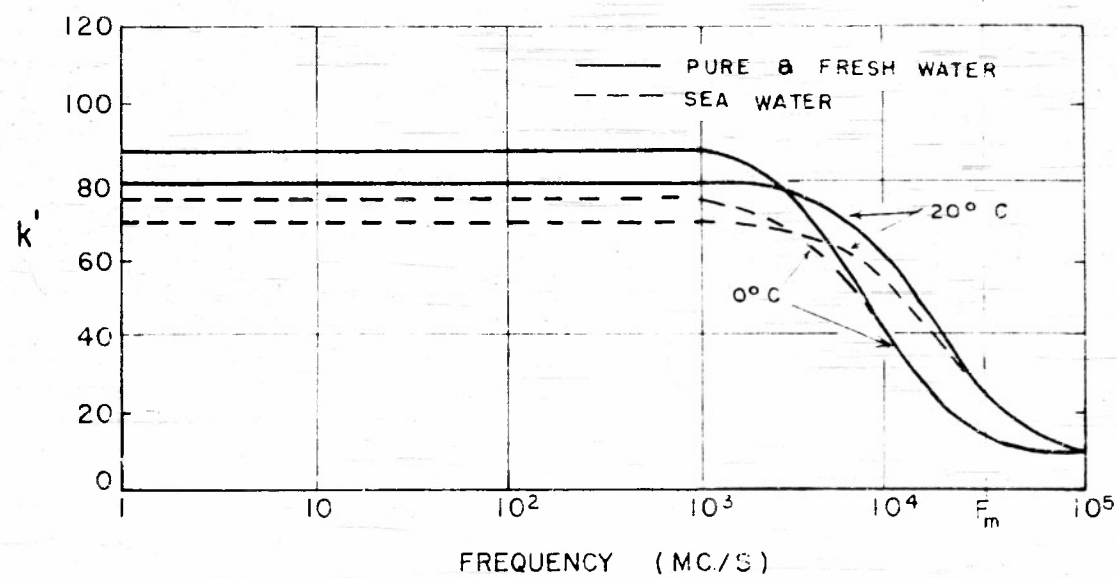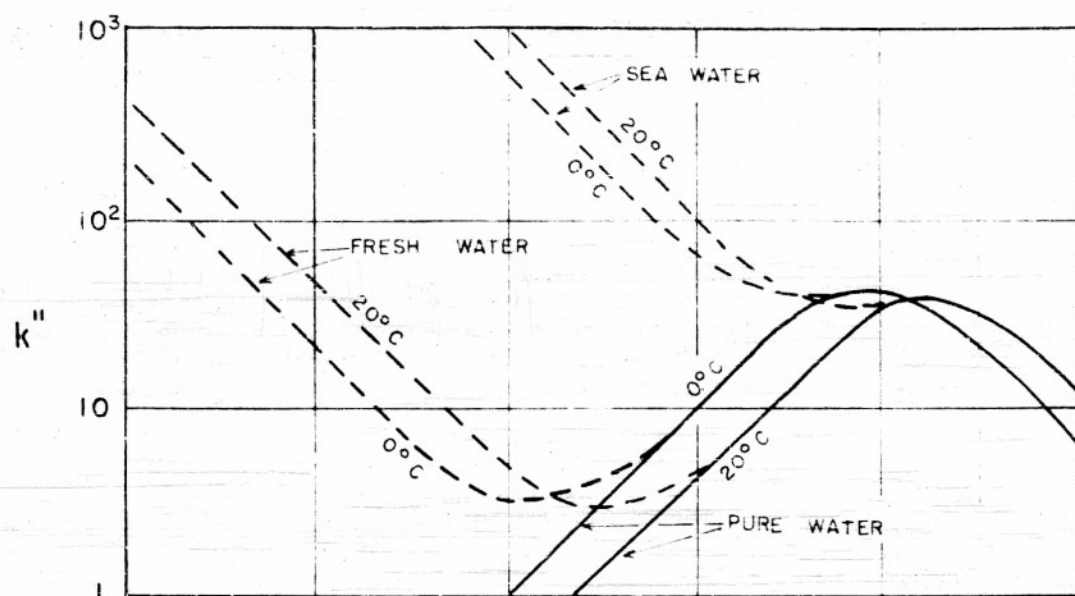
FIGURE 3

DIELECTRIC PROPERTIES OF PURE, FRESH AND SEA WATER
(Reproduced from Saxton[43])

Table I

Data and Results

Curve	Temp. °C	α Nepers Meter	β_d Rad. Meter	β Rad. Meter	C Mhos Meter	k'	k''
Distilled Water							
P1, A1	30	2095	3243	3970	60.4	21.4	31.2
P1, A3	23.5	1920	3243	3970	55.3	22.6	28.6
Theory	30	------------------------------				24.4	32.0
Theory	20	------------------------------				18.6	28.2
Saturated Salt Water Solution (About 6.2 Normal)							
P4, A4	25	1910	3170	3900	54.0	21.7	27.4
P5, A4	25	1910	3020	3750	52.0	19.5	26.8
Theory	30	--(2.0 Normal Solution)--				20.6	29.7
Tap Water							
P7, A6	24	1900	3300	4030	55.6	23.7	28.7
Ethyl Alcohol							
P8, A8	23.5	306	692	1422	3.16	3.6	1.65
Dry Soil							
P9, A9	-----	55.2	534	1264	0.506	2.98	0.26

The theoretical values for k' and k" for distilled water were not available for comparison for a temperature of 23.5°C. However, if a linear relation may be assumed between the 20 and 30 degree values, the measured value of k' will differ from the theoretical value by about 11% and k" will differ from the theoretical value by about 2.4%. Note that for the 23.5°C measurement, the measured value is high, and hence, the deviation is opposite that obtained for the measurement at 30°C.

The same distilled water sample was not used for both measurements reported. The sample measured at 30°C was obtained from the distilled water plumbing in the laboratory. The sample purity was questioned and the second sample was obtained from bottled distilled water. However, both samples showed considerable conductivity when checked by immersing ohmmeter probes in the sample. The sample measured at 23.5°C is believed to be the more reliable of the two. The curves of Figure 3 indicate that even moderate amounts of salt impurities should not be expected to have a significant affect upon the measured values of k' and k".

It will be noticed that both k' and k" are quite sensitive to temperature change in the frequency region under consideration. The deviation of the measured value from that predicted by the Saxton theory may result from temperature measurement errors.

The addition of salt appeared to cause the expected drop in both k' and k", but the change is slight and hardly within the precision of measurement.

The values of k' and k" obtained for tap water differ only slightly from that obtained for distilled water. This difference is less than the probable errors of the experiment; hence, it may be assumed that both samples have approximately the same characteristics.

XI. DIELECTRIC CONSTANT OF ETHYL ALCOHOL

A complex dielectric constant of 3.6 - j 1.63 was obtained for commercial grade ethyl alcohol at 23.5°C and 0.86 cm wavelength. This is in close agreement with the values calculated from absorption coefficient and index of refraction data obtained by Lane and Saxton [6]. From these data, values of k_c are determined as 3.45 - j 1.08 and 4.21 - j 1.55 at 20°C and wavelengths of 0.62 and 1.24 cm respectively. The value of k" obtained is higher than the values obtained by Lane and Saxton at both 0.62 and 1.24 cm wavelengths, but the value of k' obtained is in close agreement with their values.

The ethyl alcohol used was commercial grade and probably contained significant amounts of both methyl alcohol and water. Either of these impurities, if present, would result in an increase in k".

The region of dispersion for ethyl alcohol is considerably lower than the measurement frequency as is evidenced by the low value of k_c obtained. The static values of k_c is between 20 and 30 at normal temperatures.

Measured values of k_c for some polar molecules indicate that the dielectric behavior cannot be expressed by relations of the form of (38) and (39). Ethyl alcohol is one of this group. Some attempt has been made to account for discrepancies [8] by considering k_c to be given by expressions of the same form as

(38) and (39) but with a distribution of relaxation times instead of a single re-
laxation time as was assumed for water. This distribution would broaden the dis-
persive region. Saxton [9] has shown, that for his data on ethyl alcohol at least,
the distribution theory offers no closer agreement with measured data than the
single relaxation time theory.

XII. DIELECTRIC CONSTANT OF DRY AUSTIN SOIL

The soil sample was obtained from the surface soil near the laboratory site.
The soil was very dry and was tested as found. The sample was strained through a
coarse sieve to remove the large particles. Each addition of sample was loosely
packed. The temperature of the soil sample was not measured but may be consider-
ed to be room temperature which was in the range of 25 to 30°C.

The value of the dielectric constant of the soil sample at 8.6 mm wavelength
was determined to be $2.98 - j0.26$, and was found to be 0.506 mhos/meter. The die-
lectric constant agrees closely with the value of 2.8 reported by Straiton and
Tolbert [2] for 3.2 cm. The conductivity at 8.6 millimeter for the dry soil was
higher than the 3.2 cm measurements for very wet soil and 30 times greater the 3.2
cm measurements for very dry soil.

XIII. CONCLUSIONS

The measured values of the complex dielectric constant of water and salt
water solutions are approximately as predicted by the Saxton theory. The magni-
tude of the deviations observed may have resulted from temperature measurement
errors. The high sensitivity of k_c to changes in temperature is clearly illus-
trated as is the low sensitivity of k_c to salt concentration.

The value of k_c obtained for the ethyl alcohol sample is in close agreement
with values reported by others. The slight deviation present probably resulted
from water of methyl alcohol present as impurities.

The soil sample, though very dry, probably contained sufficient moisture to
influence the results obtained. Both the real and imaginary components of the
dielectric constant of the soil sample are low compared to those of water at the
frequency of measurement. Therefore, the electrical characteristics of soil may
be expected to be quite sensitive to changes in moisture content.

APPENDIX

Attenuation and Phase Shift Curves

Attenuation and phase shift plots for distilled water, salt water, tap water ethyl alcohol, and dry soil samples are presented in this appendix. From these curves, attenuation and phase shift were determined as previously described. All reasonably consistent data were plotted. When two or more sets of data determined essentially the same line the most consistent set of points was chosen and one line was drawn through these points.

FIGURE 4

ATTENUATION AND PHASE SHIFT
AS A FUNCTION OF ADDED VOLUME
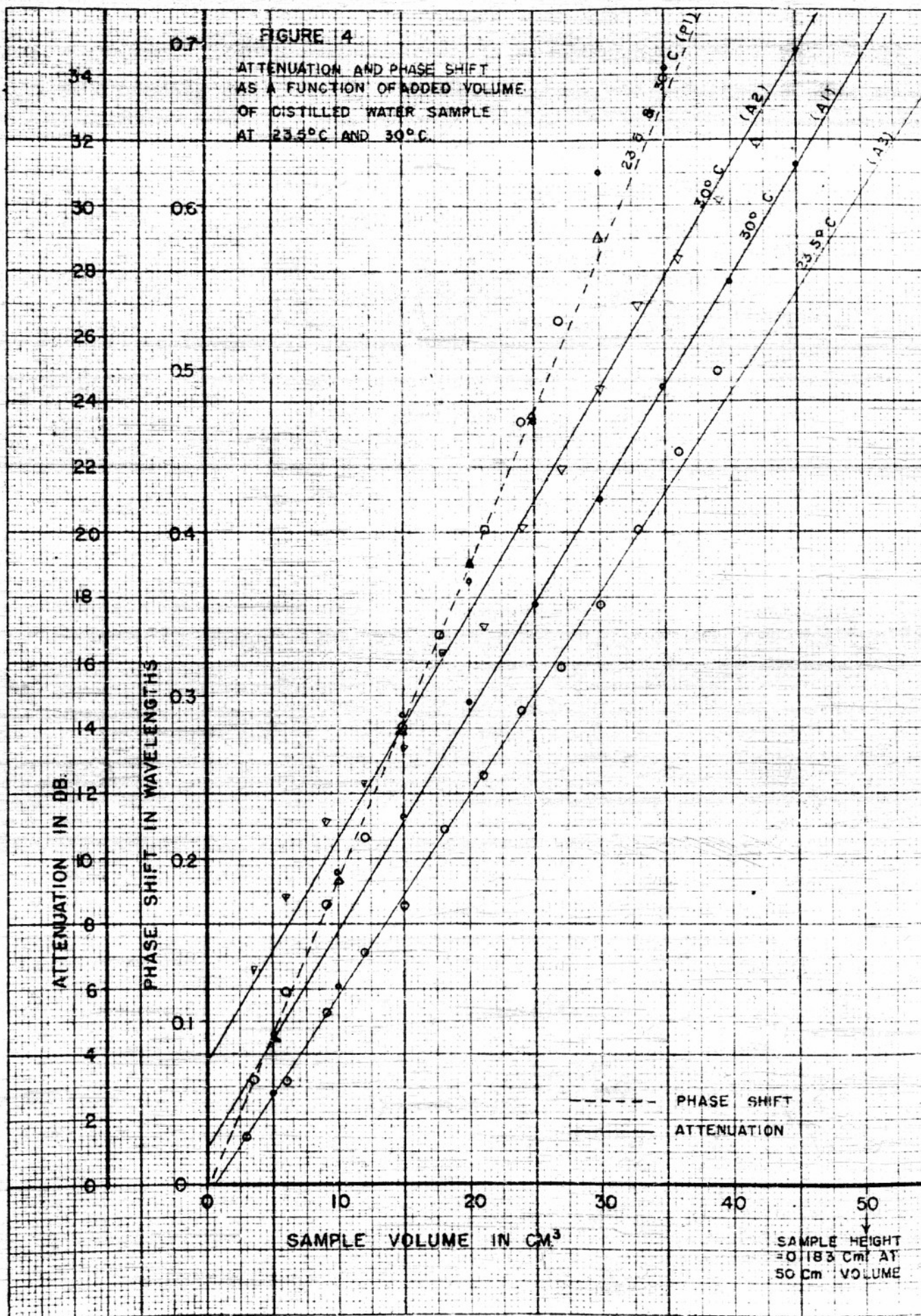OF DISTILLED WATER SAMPLE
AT 23.5°C AND 30°C.

FIGURE 5

ATTENUATION AND PHASE SHIFT
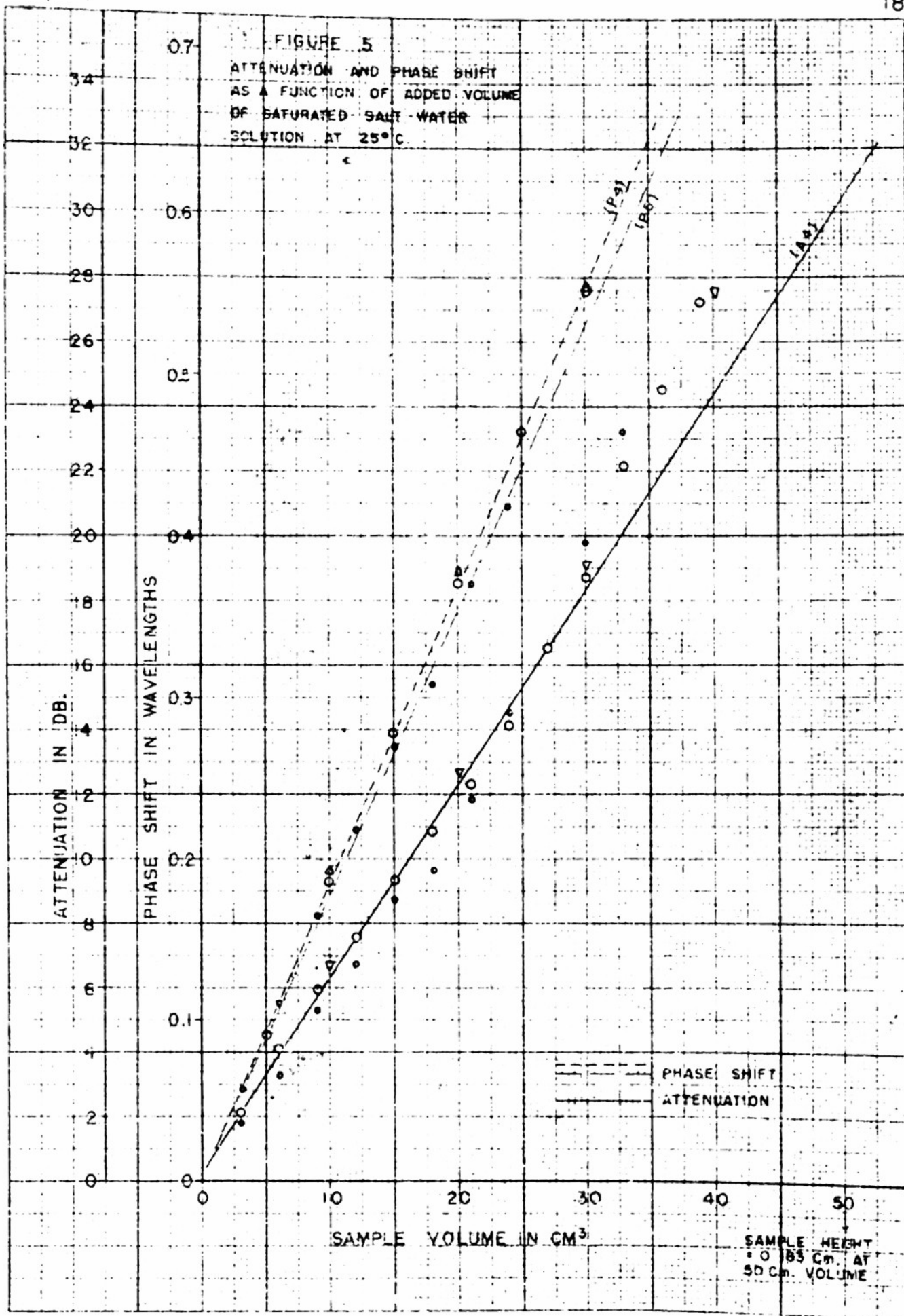AS A FUNCTION OF ADDED VOLUME
OF SATURATED SALT WATER
SOLUTION AT 25° C.

FIGURE 6

ATTENUATION AND PHASE SHIFT
AS A FUNCTION OF ADDED VOLUME
OF TAP WATER SAMPLE AT 24°C
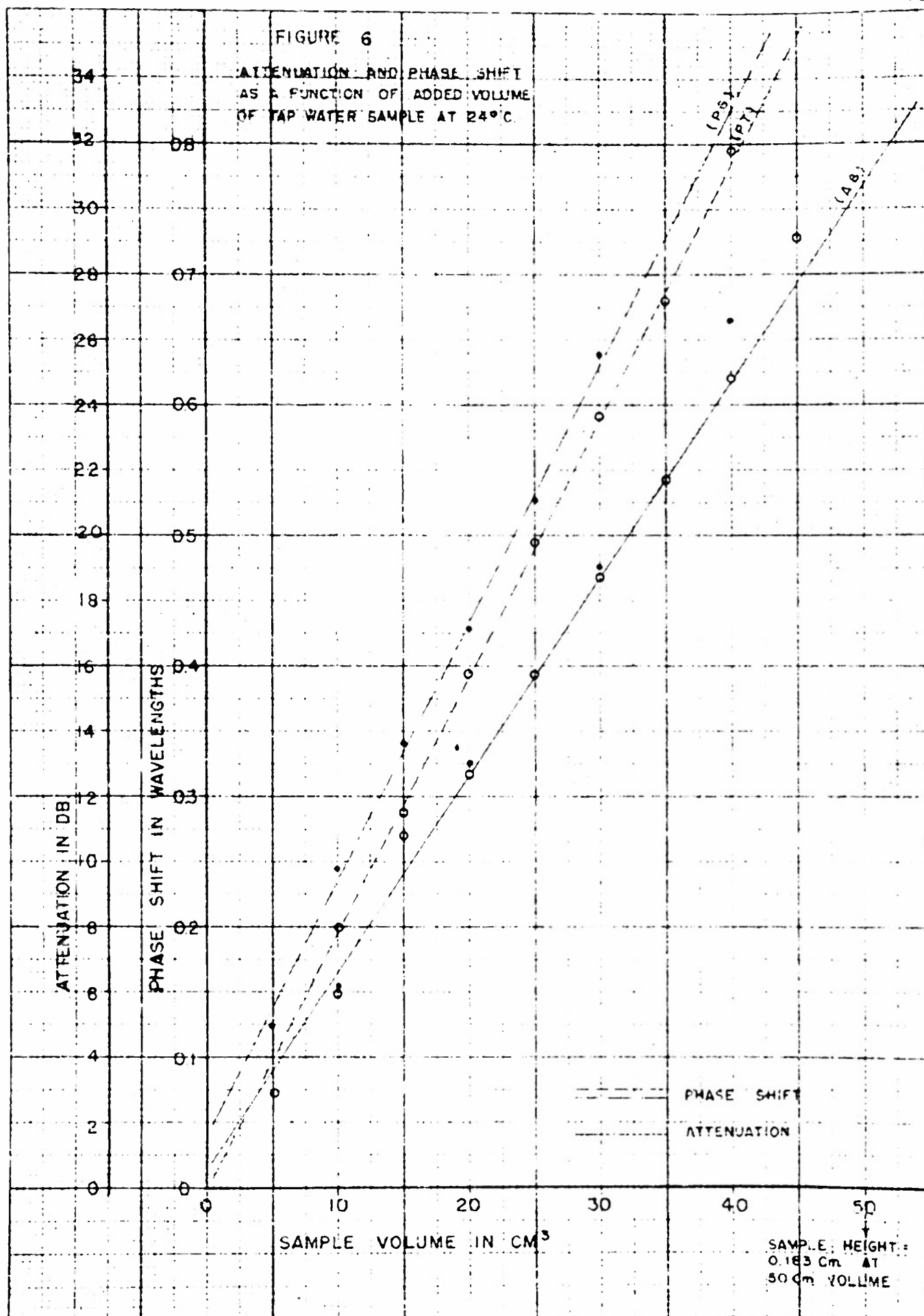
SAMPLE HEIGHT:
0.183 Cm AT
50 Cm VOLUME

FIGURE 7

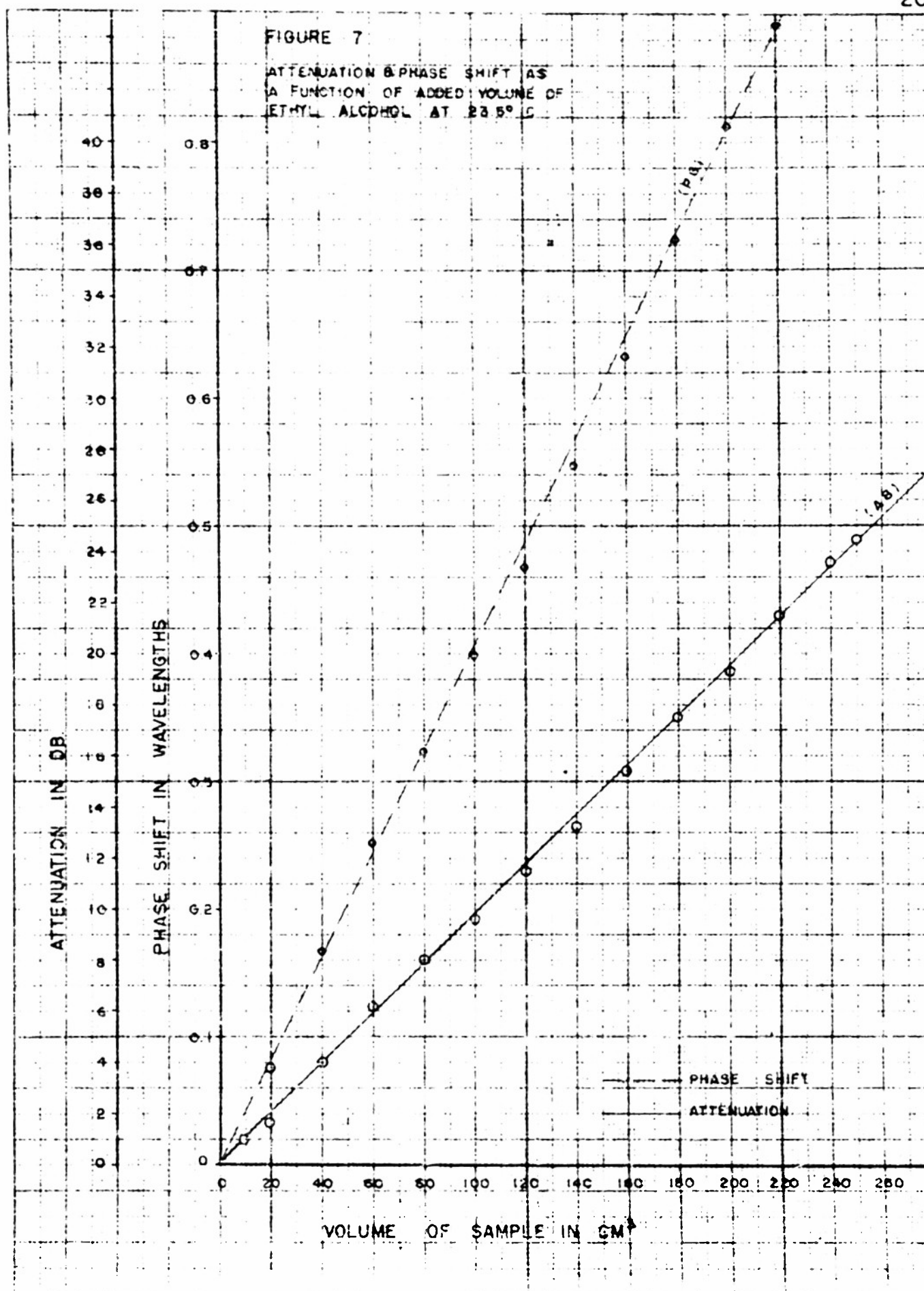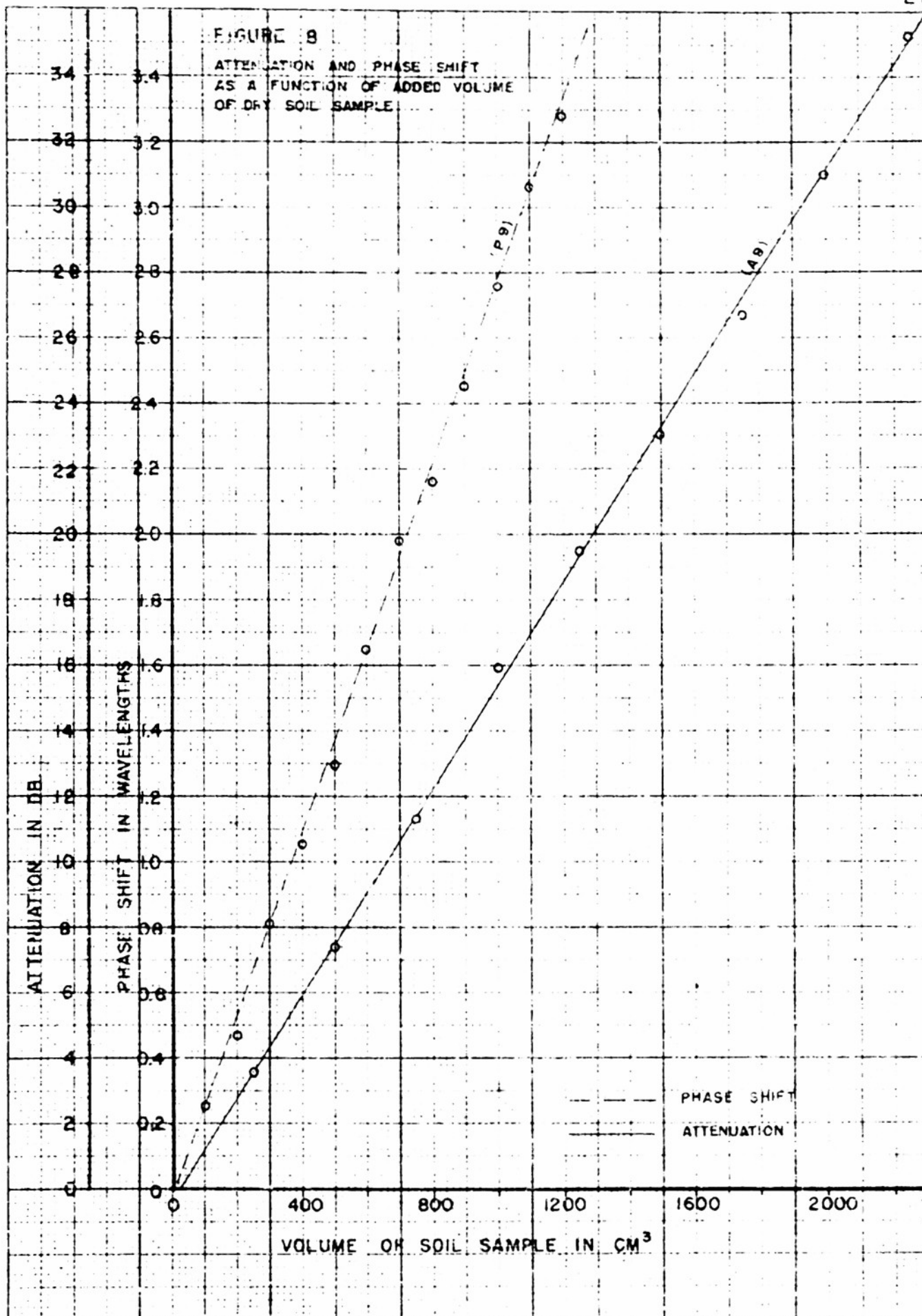ATTENUATION & PHASE SHIFT AS A FUNCTION OF ADDED VOLUME OF ETHYL ALCOHOL AT 23.5° C

FIGURE 8

ATTENUATION AND PHASE SHIFT
AS A FUNCTION OF ADDED VOLUME
OF DRY SOIL SAMPLE

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